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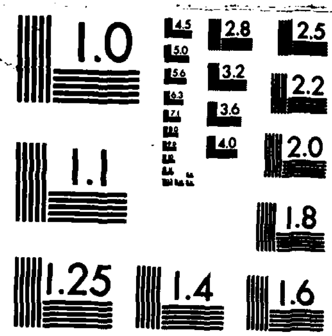

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REPORT

MRL-R-947

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A.J. Bedford

Approved for Public Release

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POSTAL ADDRESS: Director, Materials Research Laboratories
P.O. Box 50, Ascot Vale, Victoria 3032, Australia

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Plasma mass and effective inductance in a small railgun

AUTHOR(S)	CORPORATE AUTHOR
A.J. Bedford	Materials Research Laboratories P.O. Box 50, Ascot Vale, Victoria 3032

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PLASMA MASS AND EFFECTIVE INDUCTANCE IN A SMALL RAILGUN

1. INTRODUCTION

A series of railgun firings using the RAPID system [1] was conducted to assess the effect on railgun performance of different plasma-initiating foil type and mass. All firings were done using a 1600 µF capacitor bank (storing 28.8 kJ at 6 kV), 5.6 µH inductor and two spark gap switches. For each firing the capacitor bank was charged to 6 kV before closing the main switch. The railgun [1] had a bore of 6mm x 8mm (rail face to rail face) and was 500mm long. The polycarbonate projectile had the dimensions 8 x 6 x 6mm and had a nominal mass of 0.385 g.

Foils were made of Al, Zn or Cu. Our 'normal' aluminium foil was chosen as the standard value; that was a piece of 0.025 mm commercial Al foil 44 x 6 mm, folded to 11 x 6 mm. This foil, designated Al(1), weighed about 0.012 g and was glued to the back of a projectile.

Two variations from the standard foil for Al were used, one about 1/5 the mass of the standard and the other about 5 times the standard mass. These were designated Al(1/5) and Al(5) respectively.

The standard Zn foil was cut 44 x 6 mm from a 0.025 mm thick foil. It was assembled with a projectile in the same way as for the Al foils and its mass was about 0.04 g. Copper foils were cut from 0.125 mm foil and the Cu(1) standard foil weighed about 0.05 g and measured 11 x 3.4 mm. These foil masses were selected to give similar numbers of atoms in each case to provide a valid comparison between the different metals used. One-fifth and five-times variations to these foils were also used. Table 1 shows the foil types and masses as well as the total projectile + foil masses, alongside an identifying number for each firing.

TABLE 1 FOIL TYPES AND MASSES AND PROJECTILE MASSES

RPIP#	FOIL TYPE	FOIL MASS (g)	FOIL MASS + PROJECTILE MASS (g)
01	Al(1)	0.0120	0.392
02	Al(1)	0.0117	0.395
03	Zn(1)	0.0422	0.430
04	Zn(1)	0.0330	0.420
05	Cu(1)	0.0510	0.439
06	Cu(1)	0.0475	0.435
07	Zn(1/5)	0.0083	0.397
08	Zn(1/5)	0.0086	0.386
09	Cu(1/5)	0.0127	0.404
10	Cu(1/5)	0.0069	0.392
11	Al(5)	0.0612	0.449
12	Al(5)	0.0615	0.450
13	Zn(5)	0.2126	0.599
14	Cu(5)	0.1976	0.585
15	Cu(5)	0.1960	0.585
16	Zn(5)	0.2006	0.586
17	Al(1/5)	0.0025	0.374
18	Al(1/5)	0.0024	0.388
19	Al(1)	0.0122	0.397
20	Al(1)	0.0120	0.395
21	Cu(5)	0.1972	0.585
22	Zu(1/5)	0.0082	0.392
23	Cu(1/5)	0.0069	0.394
24	Al(1/5)	0.0024	0.387
25	Al(1)	0.0118	0.397
26	Cu(1/5)	0.0088	0.392

Note: The letters RPIP refer to Railgun Plasma Intensity Profile experiments.

In these experiments we planned to extract as much varied information from each firing as could be handled with the instrumentation available. Transient recorders were used to take such records as current, muzzle and breach volts versus time; others recorded time events generated as the projectile/plasma passed B-dot probes [1] on the railgun bore, and as the projectile passed various interupt devices at, and outside, the muzzle. In addition high speed streak and framing cameras [2] recorded the passage of the plasma in the railgun bore.

Extensive results were gathered from the series of 26 firings and various analyses are being attempted. We have already reported [2,10] that muzzle voltage (in effect arc voltage drop) does not appear to be affected by the type or mass of initiating foil, at least within the parameters of our experiments. Approximate values are recorded in Table 2. We are attempting to provide a better understanding of plasma behaviour in a railgun bore by doing film density probes on the streak photographs; this analysis is not

complete, but will aim to give data on, for example, plasma length versus current in the railgun.

In this report we present an analysis of L'_{eff} for each firing calculated to fit the in-bore displacement-time curves which are obtained from the streak photographs. Thus L'_{eff} is here defined as that rail inductance per unit length which when applied in the equation $F = \frac{1}{2} L'I^2$ best fits the data recorded during experiments, (see also ref. 3). The principles of the analysis are explained in the following section.

2. PRINCIPLES OF THE ANALYSIS

2.1 Streak Records and Displacement - Time Plots

A streak camera record from one of the firings is shown in Fig. 1. The long axis of the photograph is the time axis and the shorter axis records distance along the railgun bore. The front of the plasma is confined by the projectile back face and therefore appears fairly sharp, whereas with no constraint at the back, other than the magnetic field in the railgun, the back of the plasma appears rather more diffuse. By taking readings at the front or sharper edge of the film record, a displacement-time (x vs t) curve is plotted for each of the firings.

Several phenomena were observed on the streak records from these firings and more extensive analyses will be reported elsewhere. Whereas Fig. 1 shows a relatively clean streak record, Fig. 2 shows four different phenomena. Even where the various instabilities or leakages occurred it was possible to obtain an x vs t curve for the firing by measurements on the front edge of the main streak recording.

2.2 Calculation of L'_{eff}

To date, of the parameters which are used to describe or analyse railgun performance, there are two, plasma mass and rail inductance per unit length (L'), about which there is considerable uncertainty. Some of our work has been aimed at obtaining a better description of these properties and Richardson and Marshall [3] have described a simple digital computer simulation method for small calibre railguns in which they incorporated all circuit parameters. In the present analysis we have used the same basic approach but as far as possible have used actual experimental results as input to the calculations. Many of the circuit parameters are thus accounted for by using the experimental results. In addition, in the present calculations we attempt to take some account of the fact that a mass of plasma is being accelerated as well as the projectile - the previous simulation [3] assumed that the accelerated mass was the projectile only.

The following equations are used:

x-t curve is quite sensitive to the L' (and/or mass), and a good eye fit can be obtained by shifting the simulated and experimental curves to check that their shapes correspond. In this way we believe that a valid L'_{eff} is being estimated for the conditions defined in the report, and that the accuracy of these estimations is within about 0.01 for each L'_{eff} given.

The main parameter about which there is doubt (other than L' itself) in these simulations is m, the mass of projectile + plasma (neglecting any mass ahead of the projectile); ie the mass being accelerated by the electromagnetic $\underline{j} \times \underline{B}$ force. The first assumption that can be made is that all the initiating foil mass goes to make up the plamsa and so the total mass is the projectile mass + foil mass. During the present simulations we have varied the total mass value and the reasons and results are presented in the following section.

Fig. 4. shows the displacement-time curve for the firing RPIP 02 and simulated curves for different L' values. In these calculations m = 0.395 g, which is equal to the projectile mass + initiating foil mass. The calculated curve which most nearly corresponds to the experimental curve has an L' of 0.28 μH/m.

3. RESULTS OF EXPERIMENTS AND SIMULATIONS

All streak camera records for the RPIP series of firings were digitised and x vs t curves were plotted. Simulations were conducted using the I vs t values of each experiment and an effective L' obtained. In Table 2 we present L'_{eff} calculated where the mass of projectile + plasma is assumed to be the projectile mass + initiating foil mass. The second L'_{eff} column is derived from an assumption that the projectile + plasma mass is 0.4 g. These values are discussed in the following section.

Also in Table 2 we present a qualitative guide to leakage of plasma past the projectile, and a value or small range for the muzzle (or armature) voltage. This information is also used in the following discussion of results.

4. DISCUSSION

For the railgun configuration of these experiments we have used the methods proposed by Kerrisk [4,5] to calculate the maximum L' value we could expect to achieve in the absence of frictional effects. This value is 0.4 μH/m. We have confidence in this value being the best theoretical value for L' in railguns due to the rigorous nature of the Kerrisk calculations and to the fact that the Kerrisk value of .43 μH/m for the ANU railgun compares very favourably with the experimental value of 0.42 μH/m. [6,7] Table 2

TABLE 2

RESULTS OF EXPERIMENTS AND SIMULATIONS TO OBTAIN EFFECTIVE L'

Foil Type	Foil Mass (g)	RPIP #	m** (g)	L'_{eff} (μH/m)	L'_{eff} for m=0.4g (μH/m)	Plasma Leakage*	Muzzle Voltage (V)
Al(1/5)	.003	17	.376	.19	.20	S	-
	.002	18	.392	.20	.20	S	-
	.002	24	.388	-	-	S	180
Al(1)	.012	01	.392	.24	.24	S	180
	.017	02	.395	.28	.28	N	170
	.012	19	.399	.23	.23	S	-
	.012	20	.397	.23	.23	S	150-195
	.012	25	.397	.27	.27	S	195
Al(5)	.061	11	.449	.30	.27	N	-
	.062	12	.450	.33	.29	N	210-150
Cu(1/5)	.013	09	.404	.28	.28	N	-
	.007	10	.392	.23	.24	M	210-140
	.007	23	.394	.40	.40	N	-
	.009	26	.392	.23	.24	S	190
Cu(1)	.051	05	.439	.29	.26	N	190
	.048	06	.435	.32	.30	N	180
Cu(5)	.198	14	.585	.40	.27	N	-
	.196	15	.585	.40	.27	N	175
	.197	21	.585	.50	.34	N	-
Zn(1/5)	.008	07	.397	.24	.24	N	185
	.009	08	.386	.22	.23	S	-
	.008	22	.392	.33	.33	N	180
Zn(1)	.042	03	.430	.27	.25	M	175
	.033	04	.420	.31	.30	N	190
Zn(5)	.213	13	.599	.38	.25	M	180
	.201	16	.587	.40	.28	N	180

* N = none or very little
M = moderate
S = severe

** m = mass of projectile + mass of foil

5. SUMMARY AND CONCLUSIONS

In 26 firings with a small calibre plasma driven electromagnetic railgun, plasma-initiating foils of aluminium, copper and zinc were used. Projectile-in-bore displacement-time and current-time results were used to calculate an effective L' (rail inductance per unit length) for each experiment.

The principal uncertainties in railgun experiments of this kind are the plasma mass and L'. Our experiments have indicated that plasma mass reaches an equilibrium value dependent on the railgun configuration and firing conditions (input energy etc). In addition plasma initiating foil seems not to be a controlling factor; we believe that the equilibrium plasma composition is dependent only on the rail material. A railgun plasma will be in a continuous state of losing material towards its trailing edge and regenerating from the rails in the body of the plasma. These postulates are supported by the fact that muzzle (or arc) voltage is about the same, and remains substantially constant for all firings.

For the small calibre railgun used, estimates of L' are significantly below the theoretical L' and so maximum or potential performance is not achieved. As would be expected, leakage of plasma past the projectile decreases the effective L' for the firing - ie performance is degraded. This highlights the importance of obturation in railgun systems but as with any gun the trade-off with friction will be important.

6. ACKNOWLEDGEMENTS

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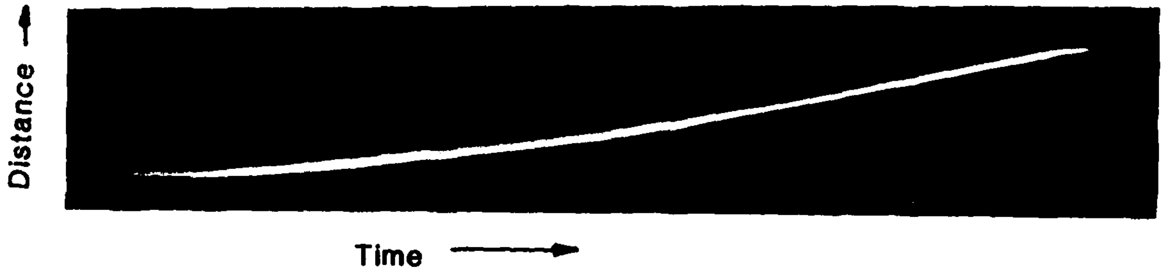

Figure 1. Streak photograph for firing RPIP 02. In Figs 1 & 2 the horizontal scale is approximately 1mm ≡ 5.5 μs and the vertical scale approximately 1mm ≡ 22 mm.

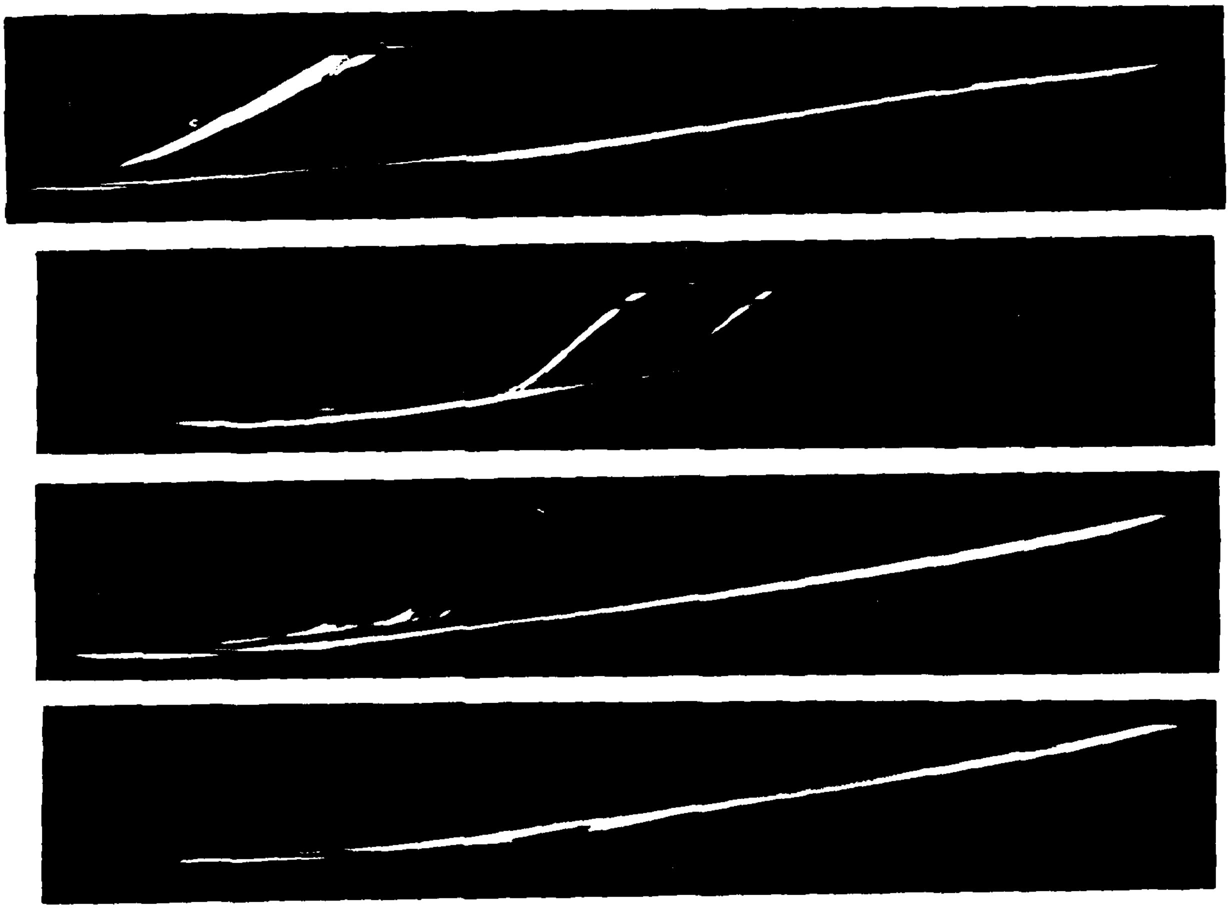

Figure 2. Streak photographs showing results for different firings in the RPIP series. (see Fig. 1 for approximate scales).

(a) pronounced plasma runaway in front of projectile
(b) two runaways effectively extinguish main plasma
(c) large amount of leakage past a projectile
(d) Significant instabilities in early part of firing with heavy foil.

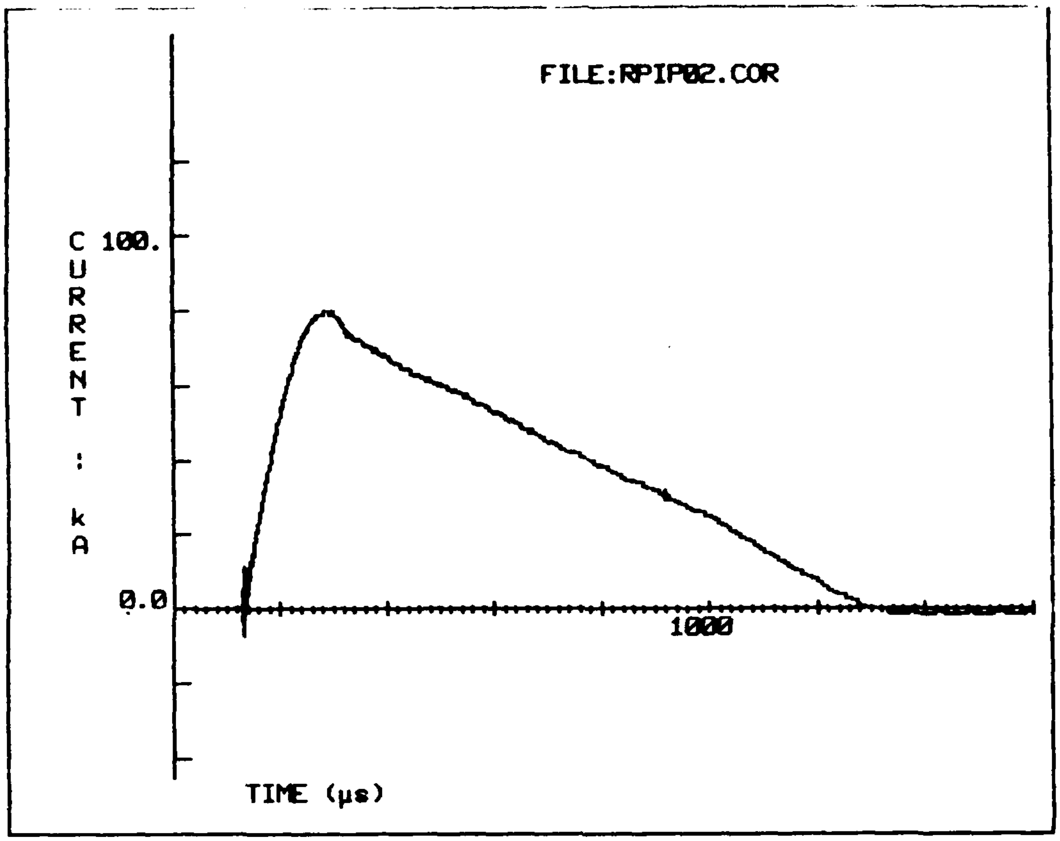

Figure 3. Current versus time curve for firing RPIP 02.

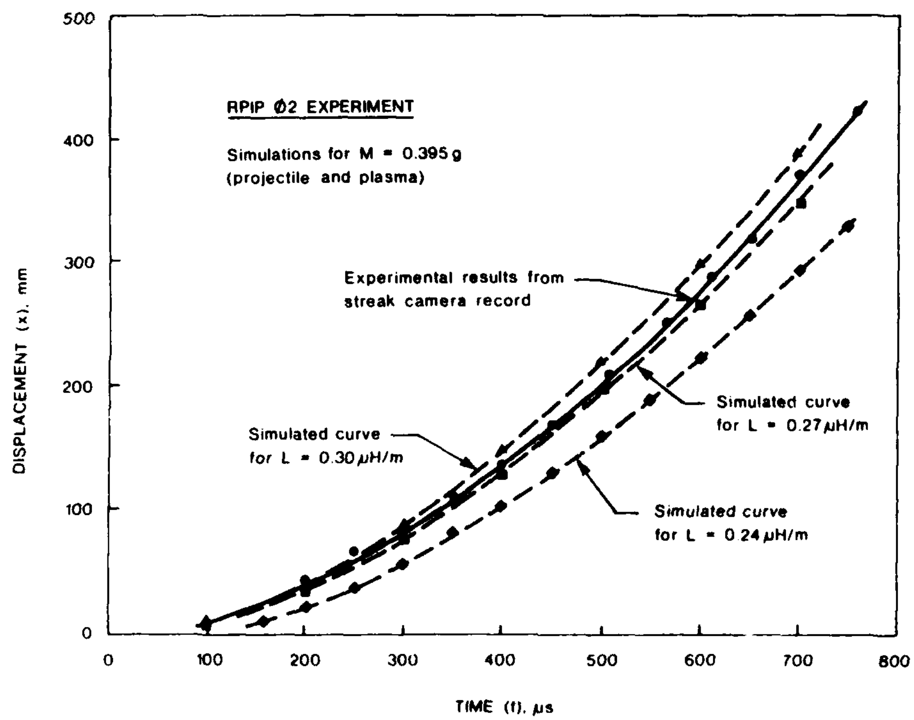

Figure 4. Displacement-time curve for RPIP 02 experiment and simulated curves for selected values of L'.

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